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SU(2)-Flavor-Symmetry Breaking
in Nuclear Antiquark Distributions

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ABSTRACT

SU(2)-flavor-symmetry breaking in antiquark distributions of the nucleon was suggested by the New Muon Collaboration (NMC) in deep inelastic muon scattering. As an independent test, Drell-Yan data for the tungsten target have been used for examining the asymmetry. We investigate whether there exists significant modification of the $\bar{u} - \bar{d}$ distribution in nuclei in a parton recombination model. It should be noted that a finite $\bar{u} - \bar{d}$ distribution is theoretically possible in nuclei even if the sea is $SU(2)_f$ symmetric in the nucleon. In neutron-excess nuclei such as the tungsten, there exist more d-valence quarks than u-valence quarks, so that more $\bar{d}$-quarks are lost than $\bar{u}$-quarks are due to parton recombinations in the small x region. Our results suggest that the nuclear modification in the tungsten is a 2–10 % effect on the $\bar{u} - \bar{d}$ distribution suggested by the NMC data. Nuclear effects on the flavor asymmetric distribution could be an interesting topic for future theoretical and experimental investigations.

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1. Introduction

It became possible to test the Gottfried sum rule [1] recently because accurate experimental data could be taken in the small x region. This sum rule is a phenomenological one based on a naive parton model. This is because we need a special assumption of the SU(2)-flavor-symmetric antiquark distributions. Therefore, even if the sum rule is broken, the QCD itself is not in danger. However, it implies an interesting physics mechanism which we cannot expect in the naive parton model.

The sum rule is described in the parton model as follows. Integrating the proton and neutron structure-function difference over x with the isospin-symmetry assumption ($u_p = d_n \equiv u$, $d_p = u_n \equiv d$, $\bar{u}_p = \bar{d}_n \equiv \bar{u}$, $\bar{d}_p = \bar{u}_n \equiv \bar{d}$), we obtain

$$S_G \equiv \int_0^1 \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] \quad . \tag{1}$$

If the antiquark distributions are $SU(2)_{flavor}$ symmetric, the second term vanishes and we obtain the Gottfried sum rule ($S_G = 1/3$).

Although there is some indication of the sum-rule breaking in the old SLAC data, it is rather surprising that the New Muon Collaboration (NMC) found large violation. They obtained the integral at $Q^2 = 4$ GeV^2 as [2]

$$\int_{0.004}^{0.8} \frac{dx}{x} [F_2^{\mu p}(x) - F_2^{\mu n}(x)] = 0.221 \pm 0.008 \pm 0.019 \quad . \tag{2}$$

Adding contributions from the unmeasured region, they found a significant deviation from the Gottfried sum rule,

$$S_G = 0.235 \pm 0.026 \quad . \tag{3}$$

This NMC result indicates that antiquark distributions are not $SU(2)_f$ symmetric and we have $\bar{d}$ excess over $\bar{u}$.

This conclusion is contrary to the naive quark model expectation, the $SU(2)_f$ symmetric sea ($\bar{u} = \bar{d}$). The symmetric distributions are expected because the sea is thought to be created perturbatively through a gluon splitting into a light quark pair, $u\bar{u}$ or $d\bar{d}$. Thus, the NMC result suggests a nonperturbative mechanism for explaining the symmetry breaking. There are theoretical candidates such as Pauli blocking models [3], mesonic models [4], and others [5].

We do not discuss these theoretical models in this paper. In spite of the NMC's claim of the flavor-symmetry breaking, there is still possibility that the result could be explained with the symmetric sea $\bar{u} = \bar{d}$. This is because the smallest x in the NMC experiment is 0.004 and the Gottfried sum rule may receive a significant contribution from the very small x region. In order to test this problem, we should wait at least several years for a possible HERA experiment at small x. Therefore, it is desirable that we have independent experimental evidence for the asymmetric antiquark distributions [6].

A possible way is to use Drell-Yan processes [7]. In fact, the Drell-Yan data for the tungsten target have been analyzed. At this stage, we cannot draw a strong conclusion from the tungsten data whether the light-quark-sea is symmetric or not. On the other hand, nuclear effects are possibly significant because the tungsten is a heavy nucleus. If the nuclear modification is very large, the Drell-Yan analysis cannot be directly compared with the NMC result.

The purpose of this paper is to investigate a possible mechanism of producing a $\bar{u} - \bar{d}$ distribution in nuclei, especially in the tungsten nucleus. In the near future, the Drell-Yan data for the proton and the deuteron targets will be taken at Fermilab, so that our prediction can be tested. There is also a recent Drell-Yan result by the CERN-NA51 collaboration, and it indicates a strong asymmetry $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ at $x = 0.18$ and $Q^2 = 20$ GeV^2 [8]. If accurate experimental results are supplied by these Drell-Yan experiments for the nucleon and also for nuclear targets, nuclear modification of the $\bar{u} - \bar{d}$ distribution could become an interesting topic. This paper is intended to shed light on such modification.

2. Nuclear effects on the $\bar{u} - \bar{d}$ distribution

We investigate the SU(2)-flavor-asymmetric distribution $(\bar{u} - \bar{d})_A$ in nuclei, especially in the tungsten nucleus. We first show "conventional" expectations without nuclear effects. If there is no asymmetry in the nucleon ($\bar{u} = \bar{d}$) and no nuclear modification, the distribution is symmetric $[(\bar{u} - \bar{d})_A = 0]$ as shown by the solid line in Fig. 1. However, if there is asymmetry in the nucleon, the distribution becomes

$$x[\bar{u}(x) - \bar{d}(x)]_A = -\varepsilon x[\bar{u}(x) - \bar{d}(x)]_{proton} \quad , \tag{1}$$

without considering nuclear modification. The neutron-excess parameter ε is defined by

$$\varepsilon = \frac{N - Z}{N + Z} \quad . \tag{2}$$

This parameter is defined so that it satisfies $\varepsilon = 0$ for isoscalar nuclei ($N = Z$) and it does $\varepsilon = 1$ for neutron matter. For example, it is 0.196 for the tungsten $^{184}_{74}W_{110}$. Isospin symmetry is assumed in the parton distributions of the proton and the neutron in Eq. (1). Using the MRS-D0 parton distributions [9], which were obtained so as to reproduce the NMC data, we get the $\bar{u} - \bar{d}$ distribution in the tungsten nucleus as shown by the dashed curve in Fig. 1.

Next, we address ourselves to nuclear modification of the distributions in Fig. 1. We discuss a mechanism of producing the asymmetric distribution $(\bar{u} - \bar{d})_A$ in nuclei even though antiquark distributions are flavor symmetric in the nucleon $[(\bar{u} - \bar{d})_N = 0]$. Because antiquark distributions are dominant in the small x region, we should first find a mechanism of nuclear shadowing for investigating nuclear antiquark distributions. There are a number of theoretical ideas for explaining the shadowing. We employ the parton-recombination model in Ref. [10] simply because the model can explain many existing data of $F_2^A(x, Q^2)$.

In the parton picture, partons in different nucleons could interact in a nucleus. These interactions are especially important at small x with the following reason. In an infinite momentum frame, the average longitudinal nucleon separation in a Lorentz contracted nucleus is L=(2 fm)M_A/P_A=(2 fm)m_N/p_N, and the longitudinal localization size of a parton with momentum xp_N is $\Delta L = 1/(xp_N)$. If the parton dimension exceeds the average separation ($\Delta L > L$) in the small x region ($x < 0.1$), partons from different nucleons could interact. This is an extra effect which does not exist in a single nucleon. The interaction is called parton recombination or parton fusion. In discussing antiquark distributions in nuclei, this effect should be taken into account properly. The recombination contributions to an antiquark distribution are given in the appendix. There are three physics ingredients in Eq. (A.3). The first and the second integrals are from interactions of an antiquark $\bar{q}_i$ in the nucleon $n1$ with a gluon in the nucleon $n2$; the third and the sixth integrals are from those of an antiquark $\bar{q}_i$ in the nucleon $n1$ with a quark q_i in the nucleon $n2$; the forth and the fifth integrals are from those of a gluon in the nucleon $n1$ with an antiquark $\bar{q}_i$ in the nucleon $n2$.

The lengthy equation becomes simpler if we assume that antiquark distributions in the nucleon are $SU(2)_f$ symmetric ($\bar{u} = \bar{d}$) and that the leak-out quark (q^*) is a sea quark with the $SU(2)_f$ symmetry ($u^*_{sea} = d^*_{sea}$). Obviously, most terms in $[\bar{u}(x) - \bar{d}(x)]_A$ vanish except for the last integral. Under these assumptions, modification of the flavor asymmetry in a nucleus becomes

$$x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]_A = \varepsilon\frac{4K}{9}x\int_0^1 dx_2\; x\bar{u}^*(x)\; x_2[u_v(x_2) - d_v(x_2)]\; \frac{x^2 + x_2^2}{(x + x_2)^4}\quad, \qquad (3)$$

where $u_v(x)$ and $d_v(x)$ are u and d valence-quark distributions in the proton. Now the meaning of creating the flavor asymmetry in nuclei becomes clear. In a neutron-excess nucleus ($\varepsilon > 0$), the d_v quark number is larger than the u_v quark one. Hence, more $\bar{d}$ quarks are lost than $\bar{u}$ quarks in the parton recombination process $\bar{q}q \longrightarrow G$. This situation is illustrated in Fig. 2. The modification of the flavor-asymmetric distribution is directly proportional to the neutron-excess parameter. Hence, the nuclear modification is $SU(2)_f$ symmetric in isoscalar nuclei ($\varepsilon = 0$), and it becomes larger as the neutron excess increases.

We evaluate Eqs. (3) and (A.3) with the input parton distributions MRS-D0 (1993) [9], Q^2=4 GeV^2, Λ=0.2 GeV in α_s, n_f=3 (number of flavor), and z_0=2 fm (cutoff for parton leaking, see Ref. [10] for details) in the tungsten nucleus $^{184}_{74}W_{110}$ ($\varepsilon = 0.196$). In evaluating Eq. (3), the $SU(2)_f$ symmetric sea in the nucleon is used by setting $\Delta = 0$ in the MRS-D0 distribution. Obtained results are shown in Fig. 3, where the solid curve shows the $x[\Delta\bar{u} - \Delta\bar{d}]_A$ distribution (per nucleon) of the tungsten nucleus in Eq. (3) with the $SU(2)_f$ symmetric sea in the nucleon, and the dashed curve shows the one in Eq. (A.3) with the $SU(2)_f$ asymmetric sea distributions as the input.

As expected in a neutron-excess nucleus, the parton recombinations produce a finite $SU(2)_f$-breaking antiquark distribution even if antiquark distributions are $SU(2)_f$ symmetric in the nucleon. Furthermore, it is a positive contribution to $\bar{u} - \bar{d}$ because of the d-valence-quark excess over u-valence in the neutron-excess nucleus. We briefly comment on Q^2 dependence of our calculation. Even though explicit Q^2 dependence is not shown in Eq. (3), the dependence is included in the factor K and in parton distributions $p(x, Q^2)$. Because the factor K is proportional to $\alpha_s(Q^2)/Q^2$, the nuclear flavor asymmetry may seem to be very large at small Q^2. However, the quark distribution $u_v(x) - d_v(x)$ in Eq. (3) becomes very small in the small x region, so that the overall Q^2 dependence is not so significant. There are merely factor-of-two differences between the asymmetric distribution at Q^2=4 GeV^2 and the one at $Q^2 \approx 1$ GeV^2.

The situation is changed if the $SU(2)_f$ asymmetric distribution is used as the input distribution. In this case, all the process in Eq. (A.3) contribute and others become as large as the $q\bar{q} \to G$ contribution. Because pn (proton-neutron) and np recombination contributions cancel, the flavor asymmetry is given by

$$x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]_A = -(w_{nn} - w_{pp})x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]_{pp}\quad, \qquad (4)$$

where w_{nn} and w_{pp} are neutron-neutron and proton-proton recombination probabilities in Eq. (A.2). Their difference is equal to the neutron-excess parameter, $w_{nn} - w_{pp} = \varepsilon$.

$[\bar{u}(x) - \bar{d}(x)]_{pp}$ is the asymmetry produced in the proton-proton recombination. The $q\bar{q} \to G$ contribution in the sixth integral of Eq. (A.3) to $[\bar{u}(x) - \bar{d}(x)]_A$ is positive as we found in the $SU(2)_f$-symmetric input case. However, it is partly canceled by the $q\bar{q} \to G$ contribution in the third integral due to the input-sea-quark asymmetry. Furthermore, $\bar{q}G \to \bar{q}$ contributions in the second and the fifth integrals are larger than the sixth integral at small x, and they are negative due to the $\bar{d}$-excess over $\bar{u}$ in the proton. Summing up these contributions, we find $\bar{d}$-excess over $\bar{u}$ in the small x region ($x < 0.01$) as shown in Fig. 3. On the contrary, we find $\bar{u}$-excess over $\bar{d}$ in the larger x region ($x > 0.05$) because $\bar{q}G \to \bar{q}$ processes in the first and the fourth integrals dominate the contribution. Without considering these nuclear effects, we obtained the asymmetry in the tungsten nucleus in Fig. 1 ($Max[x\bar{u}(x) - x\bar{d}(x)]_A \approx +0.005$). The nuclear modifications are shown in Fig. 3 ($Max[x\bar{u}(x) - x\bar{d}(x)]_A \approx +0.0001\ or\ +0.00025$). Considering the factor of two coming from the Q^2 dependence, we find that the nuclear modification is of the order of 2%–10% compared with the asymmetry suggested by the MRS-D0 distribution. In this way, even though nuclear modification is rather small, the $SU(2)_f$ asymmetry in antiquark distributions is very interesting quantity for testing underlying nuclear dynamics.

3. Conclusions

We investigated nuclear effects on the $SU(2)$-flavor-symmetry in antiquark distributions. As a result, it is interesting to find that a finite flavor-breaking distribution in a nucleus ($[\bar{u}(x) - \bar{d}(x)]_A \neq 0$) is possible even though it is symmetric in the nucleon ($\bar{u}(x) - \bar{d}(x) = 0$). According to our recombination model, the nuclear effects on $[\bar{u}(x) - \bar{d}(x)]_A$ are of the order of 2%–10% compared with the one estimated by the NMC flavor asymmetry in the nucleon. Because the Drell-Yan experiments on the proton and deuteron targets will be done at Fermilab in the near future, it is in principle possible to study the nuclear modification experimentally. The nuclear effects are important for testing underlying nuclear dynamics, and studies of these nuclear effects may help to understand the physics origin of the flavor asymmetry in the nucleon. The author hopes that this paper motivates theorists and experimentalists for investigating further details of nuclear $\bar{u} - \bar{d}$ distributions.

Appendix

Parton recombination effects on the antiquark distribution $\bar{q}_i(x)$ are given by

$$x\cdot\Delta\bar{q}_{i,A}(x) = w_{pp}x\cdot\Delta\bar{q}_{i,pp}(x) + w_{pn}x\cdot\Delta\bar{q}_{i,pn}(x) + w_{np}x\cdot\Delta\bar{q}_{i,np}(x) + w_{nn}x\cdot\Delta\bar{q}_{i,nn}(x) ,$$
$$(A.1)$$

where

$$w_{pp} = \frac{Z(Z-1)}{A(A-1)} , \quad w_{pn} = \frac{ZN}{A(A-1)} , \quad w_{np} = \frac{NZ}{A(A-1)} , \quad w_{nn} = \frac{N(N-1)}{A(A-1)} , \quad (A.2)$$

are the combination probabilities of two nucleons. For example, w_{pp} is the probability of a proton-proton combination. $\Delta\bar{q}_{i,n1\,n2}(x)$ is the modification of the antiquark distribution with flavor i due to a parton interaction in the nucleon $n1$ with a parton in the nucleon $n2$. The details of the recombination mechanism is in Ref. [10]. We simply employ the recombination result

$$x\cdot\Delta\bar{q}_{i,n1\,n2}(x) = +\frac{K}{6}\int_0^x \frac{dx_2}{x_2}\left[(x-x_2)\bar{q}_{i,n1}(x-x_2)\left\{1+(\frac{x-x_2}{x})^2\right\}\right.$$

$$\left. - x\bar{q}_{i,n1}(x)\,\frac{x}{x+x_2}\left\{1+(\frac{x}{x+x_2})^2\right\}\right]x_2 G_{n2}^*(x_2)$$

$$-\frac{K}{6}\int_x^1 \frac{dx_2}{x_2}\,x\bar{q}_{i,n1}(x)\,x_2 G_{n2}^*(x_2)\,\frac{x}{x+x_2}\left\{1+(\frac{x}{x+x_2})^2\right\}$$

$$-\frac{4K}{9}x\int_0^1 dx_2\,x\bar{q}_{i,n1}(x)\,x_2 q_{i,n2}^*(x_2)\,\frac{x^2+x_2^2}{(x+x_2)^4}$$

$$+\frac{K}{6}\int_0^x \frac{dx_1}{x_1}\,x_1 G_{n1}(x_1)\left[(x-x_1)\bar{q}_{i,n2}^*(x-x_1)\left\{1+(\frac{x-x_1}{x})^2\right\}\right.$$

$$\left. - x\bar{q}_{i,n2}^*(x)\,\frac{x}{x+x_1}\left\{1+(\frac{x}{x+x_1})^2\right\}\right]$$

$$-\frac{K}{6}\int_x^1 \frac{dx_1}{x_1}\,x_1 G_{n1}(x_1)\,x\bar{q}_{i,n2}^*(x)\,\frac{x}{x+x_1}\left\{1+(\frac{x}{x+x_1})^2\right\}$$

$$-\frac{4K}{9}x\int_0^1 dx_2\,x\bar{q}_{i,n1}^*(x)\,x_2 q_{i,n2}(x_2)\,\frac{x^2+x_2^2}{(x+x_2)^4} . \qquad (A.3)$$

The asterisk mark indicates a leak-out parton and K is given as $K = 9A^{1/3}\alpha_s(Q^2)/(2R_0^2 Q^2)$ with $R_0 = 1.1$ fm.

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Figure Captions

Fig. 1 The dashed curve shows the $x[\bar{u}(x)-\bar{d}(x)]_A$ distribution in the tungsten nucleus according to the MRS-D0 distribution. No nuclear modification is considered. Because of the neutron excess, $\bar{u}(x)$ is larger than $\bar{d}(x)$ on the contrary to the proton case. If there is no flavor asymmetry in the nucleon and no nuclear modification, we obtain no flavor asymmetry in the nucleus as shown by the solid line.

Fig. 2 Schematic pictures of parton-recombination processes. Due to d-valence-quark excess over u-valence in a neutron-excess nucleus, more $\bar{d}$ quarks are lost than $\bar{u}$ quarks are in the recombination process.

Fig. 3 Parton-recombination effects on the flavor distribution $x[\bar{u}(x) - \bar{d}(x)]_A$ in the tungsten nucleus. The solid curve is calculated by using $SU(2)_f$ symmetric antiquark distributions and the dashed one is by $SU(2)_f$ asymmetric antiquark distributions given by the MRS-D0 parametrization. It is interesting to find a finite $\bar{u} - \bar{d}$ distribution even if antiquark distributions are $SU(2)_f$ symmetric in the nucleon.

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